

ON THE METAL RICHNESS OF M DWARFS WITH PLANETS

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ABSTRACT

Knowledge of the metallicities of M dwarfs rests predominantly on the photometric calibration of Bonfils and collaborators, which predicts that M dwarfs in the solar neighborhood, including those with known planets, are systematically metal poor compared to their higher-mass counterparts. We test this prediction using a volume-limited sample of low-mass stars, together with a subset of M dwarfs with high-metallicity, F, G, and K wide binary companions. We find that the Bonfils et al. photometric calibration systematically underestimates the metallicities of our high-metallicity M dwarfs by an average of 0.32 dex. We derive a new photometric metallicity calibration and show that M dwarfs with planets appear to be systematically metal rich, a result that is consistent with the metallicity distribution of FGK dwarfs with planets.

Key words: planetary systems – stars: abundances – stars: late-type

Online-only material: color figures

1. MOTIVATION

Mass and chemical composition play central roles in the birth, evolution, and fate of stars. The growing ensemble of known exoplanets discovered by Doppler surveys has revealed that the influences of stellar mass and metallicity are not limited to the stars themselves, but also extend to their planets. Abundance analyses of the stellar samples encompassed by Doppler surveys show that the occurrence rate of detectable planets correlates strongly with stellar metallicity (Santos et al. 2004; Fischer & Valenti 2005) and stellar mass (Lovis & Mayor 2007; Johnson et al. 2007).

In the standard core accretion model of planet formation the relationships between stellar properties and the frequency of exoplanets are a reflection of the properties of the protoplanetary disk. Stars with higher metallicities have disks containing a greater abundance of refractory material in the form of dust, allowing rocky and icy cores to grow more rapidly (Ida & Lin 2004). Similarly, the disks around massive stars also have enhanced surface densities, as well as expansive radial regions in which protoplanetary cores grow most efficiently (Laughlin et al. 2004; Ida & Lin 2005; Kennedy & Kenyon 2008).

The relationship between stellar mass and exoplanet occurrence was first revealed by the paucity of Jovian planets around M dwarfs (Endl et al. 2003; Butler et al. 2006; Johnson et al. 2007). However, unlike F, G, and K (FGK) dwarfs, accurate spectroscopic metallicities are difficult to measure for M dwarfs because their spectra display complex and extensive molecular bands that leave no definable continuum, and because of limited knowledge of the millions of transitions responsible for the molecular absorption lines (Gustafsson 1989). The lack of spectroscopic metallicity measurements makes it unclear whether stellar mass or metallicity represents the root cause of the dearth of Jovian planets around M dwarfs.

Efforts have been made to calibrate the spectral features of low-mass stars by inferring the metallicities of M dwarf secondaries from their binary association with FGK primaries

(e.g., Martinache et al. 2009), or by the direct modeling of atomic lines from high-resolution spectra (Woolf & Wallerstein 2006; Bean et al. 2006; Maness et al. 2007). Unfortunately, these efforts have so far been limited to a few specific stars and/or low metallicities.

Another approach makes use of a broadband photometric calibration. The relationship between mass and absolute infrared magnitude is very tight for the lower main sequence (MS), with little dispersion seen beyond measurement errors (Delfosse et al. 2000). On the other hand, the relation between mass and absolute V-band magnitude displays a large dispersion, and Delfosse et al. suggested metallicity variations as the cause of the observed scatter. This is because increased stellar metal content leads to increased line blanketing in the blue portion of the spectrum, causing metal-rich stars to move redward in the H–R diagram such that they lie “above” the MS, e.g., more luminous than metal-poor stars of the same color.

The scatter observed by Delfosse et al. is also clearly seen in the dispersion about the MS in the $\{V - K_S, M_{K_S}\}$ plane. Bonfils et al. (2005, hereafter B05) exploited the relationship between stellar metallicity and distance away from a fiducial MS and derived a broadband, photometric (V, K_S) metallicity relation. B05 calibrated their polynomial relationship using the set of low-metallicity M dwarfs in the Woolf & Wallerstein (2006) sample, as well as M dwarfs with FGK binary companions. The metallicities of the latter sample were anchored to abundances derived spectroscopically for their corresponding FGK binary companions, under the assumption that the binary components are coeval and share the same chemical compositions.

The B05 calibration yields two remarkable results. First, M dwarfs with planets appear to be metal poor compared to more massive FGK planet host stars. When applied to the seven M dwarf planet hosts with accurate parallaxes, the B05 relationship yields a mean $[\text{Fe}/\text{H}] = -0.11$, with only a single metal-rich host star, Gl 849. This result stands in stark contrast to the sample of Sun-like stars with planets, which have a mean $[\text{Fe}/\text{H}] = +0.15$.⁴ Second, for a volume-limited sample of 47 M

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⁴ <http://exoplanets.org>.

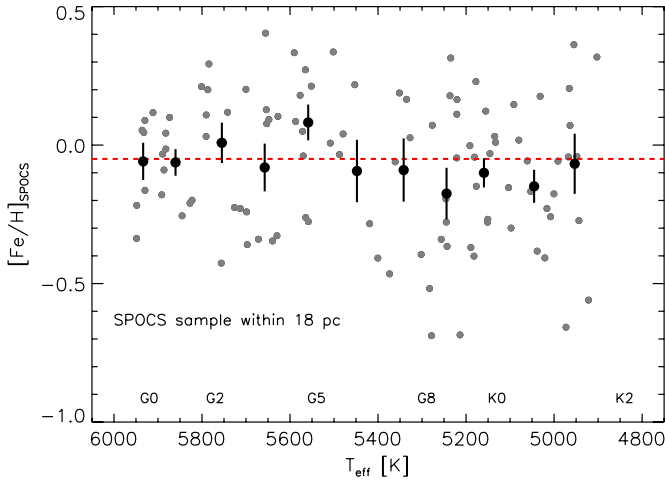


Figure 1. Metallicity distribution as a function of effective temperature for all single stars in the SPOCS catalog with $d < 18$ pc (gray circles). The large circles are the metallicities averaged within 100 K bins, and the error bars are the standard deviation of the mean $[\text{Fe}/\text{H}]$ in each bin. The dashed line is the mean metallicity for the whole sample ($[\text{Fe}/\text{H}] = -0.05$).

(A color version of this figure is available in the online journal.)

dwarfs, B05 found a mean metallicity $[\text{Fe}/\text{H}] = -0.17$, which is 0.09 dex lower than their volume-limited sample of FGK dwarfs. This implies that the metallicities of low-mass stars in the solar neighborhood are systematically lower than the Sun-like stars, which leaves open the possibility that the decreased frequency of Jupiters around M dwarfs is a reflection of their lower metallicities rather than their lower masses.

B05 suggested that their observed metallicity offset between M dwarfs and FGK stars is to be expected since M dwarfs have lifetimes longer than the age of the Galactic thin disk (e.g., < 9 Gyr; Sandage et al. 2003; del Peloso et al. 2005) and should therefore trace the Galaxy’s metal-poor past. However, K- and G-type stars also have lifetimes longer than the age of the Galactic disk (Hansen & Kawaler 1994), and yet show no metallicity offset compared to more massive, shorter-lived stars (cf. Figure 8 of Fischer & Valenti 2005). To examine the relationship between metallicity and spectral type further, we compiled a representative sample of nearby, K2-G0 stars from the Spectroscopic Properties of Cool Stars catalog (SPOCS; Valenti & Fischer 2005). To approximate a volume-limited sample we used the absolute magnitude cuts described by Reid et al. (2007, $4.0 < M_V < 6.5$) and the distance limit ($d < 18$ pc) used by Fischer & Valenti for their volume-limited subsamples of the SPOCS catalog.

Figure 1 shows metallicity versus effective temperature (spectral type) for our volume-limited subsample of 109 stars. These stars, like M dwarfs, have lifetimes longer than the age of the Galactic disk. Examination of the metallicity distribution reveals no obvious decline in $[\text{Fe}/\text{H}]$ with decreasing T_{eff} . We calculated the Pearson correlation coefficient between $[\text{Fe}/\text{H}]$ and T_{eff} and found 0.07, indicating little to no correlation between those properties among nearby stars. Thus, there does not appear to be a physical reason for M dwarfs to be systematically metal poor compared to other stars in the solar neighborhood.

In this paper we investigate the validity of the photometric calibration of B05 to ascertain whether the metallicity offset for M dwarfs is real, or the result of a systematic error in their photometric calibration. By addressing this issue, we aim to disentangle the effects of mass and metallicity as the root cause of the relative scarcity of Jovian planets around M stars.

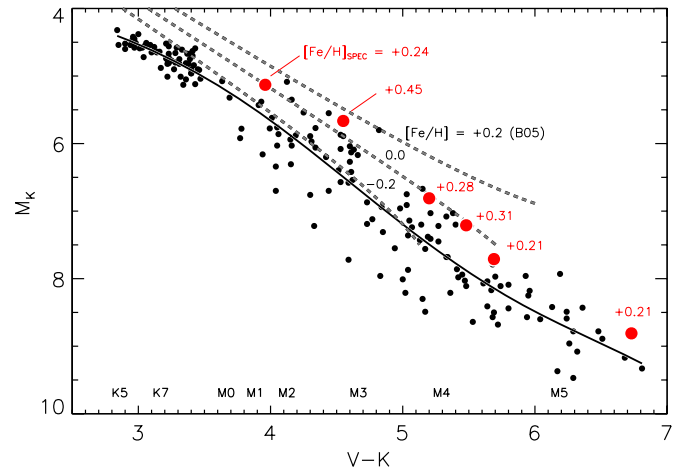


Figure 2. Nearby low-mass stars in the $\{V - K_S, M_{K_S}\}$ plane. The small black circles represent our volume-limited sample of single K dwarfs ($M_K \lesssim 5.5$, $d < 20$ pc) and M dwarfs ($d < 20$ pc). The solid line is a fifth-order polynomial fit to the mean MS. The dashed lines are the isometallicity contours from the Bonfils et al. (2005) photometric metallicity calibration. The large filled circles are the positions of a sample of high-metallicity M dwarfs, with spectroscopic $[\text{Fe}/\text{H}]$ measured from their FGK binary companions. The $V - K_S$ colors of various spectral types are listed at the bottom of the figure.

(A color version of this figure is available in the online journal.)

2. THE $V - K$ VERSUS M_K PLANE

In this section we examine the B05 calibration using test stars drawn from two volume-limited samples. The first sample is composed of single M dwarfs within 10 pc and the second sample consists of single, late K dwarfs within 20 pc. In what follows we use these two stellar samples to measure the location of the mean MS for low-mass stars in the solar neighborhood.

For our sample of K dwarfs we selected single stars with Hipparcos-based parallaxes $\pi > 50$ mas (van Leeuwen 2007), parallax uncertainties $< 5\%$, and colors $2.8 < V - K_S < 3.5$. We obtained V -band magnitudes from Hipparcos and K_S -band magnitudes from the Two Micron All Sky Survey (2MASS) catalog (Skrutskie et al. 2006). Our sample of M dwarfs comprises all known single stars with published parallaxes > 100 mas. Parallaxes and V -band magnitudes of our sample of M dwarfs are primarily from the Hipparcos Catalog or the Yale Parallax Catalogue (van Altena et al. 1995), and the K_S -band magnitudes are from Hipparcos and 2MASS, or in a few cases Leggett (1992), after applying the transformation of Carpenter (2001) to transform K_{CTT} to K_S .

Figure 2 illustrates the $\{V - K_S, M_{K_S}\}$ plane for our sample of late-type stars. Also plotted is our fifth-order polynomial fit (solid line) that denotes the mean MS for the solar neighborhood, given by $\sum a_i (V - K_S)^i$ where $a = \{-9.58933, 17.3952, -8.88365, 2.22598, -0.258854, 0.0113399\}$. Also shown are the isometallicity contours of the B05 calibration for $[\text{Fe}/\text{H}] = \{-0.2, 0.0, +0.2\}$, from bottom to top. Most of the stars in our sample lie below the B05 solar-metallicity contour, illustrating the result from B05 that most nearby M dwarfs are metal poor.

We used the B05 calibration to derive metallicity estimates for all of stars within the color and magnitude ranges over which the calibration is valid, namely $2.5 < V - K_S < 6.0$ and $4.0 < M_{K_S} < 7.5$. For the 66 stars that meet these criteria we find a mean $[\text{Fe}/\text{H}]$ of -0.2 , with only 5 metal-rich stars ($7.5 \pm 3.4\%$ with $[\text{Fe}/\text{H}] > 0$). In contrast, $41\% \pm 6\%$ of the K0-G0 dwarfs in our volume-limited subsample of the SPOCS catalog are metal rich (Figure 1). Similarly, Reid et al. (2002)

Table 1
High-Metallicity M Dwarfs

Star Name	Gliese Number	Spectral Type	M_{K_S}	$V - K_S$	ΔM_{K_S}	Spectroscopic [Fe/H]	B05 Calibration [Fe/H]
HD 46375 B		M1	5.13	3.96	0.48	+0.24	+0.00
HD 38529 B		M3	5.66	4.55	0.67	+0.45	+0.03
HD 18143 C	118.2	M4	6.81	5.20	0.68	+0.28	-0.02
55 Cnc B	324 B	M4	7.21	5.48	0.67	+0.31	-0.01
HD 190360 B	777 B	M4.5	7.71	5.69	0.43	+0.21	-0.03
Proxima Cen	551 C	M5.5	8.81	6.73	0.36	+0.21	+0.07

find that $45\% \pm 3\%$ of FGK stars in the solar neighborhood have $[\text{Fe}/\text{H}] > 0$, and Haywood (2001) estimate that roughly half of the nearby K dwarfs are metal rich. Thus, applying the B05 metallicity relationship to our sample of nearby M dwarfs suggests a large abundance offset between solar-type dwarfs and M stars.

2.1. Testing the B05 Calibration

Also shown in Figure 2 is a separate set of M dwarfs that have wide, common-proper-motion FGK binary companions with precise spectroscopic metallicity measurements (red circles). These six FGK+M binaries were selected from the SPOCS catalog and have Hipparcos parallaxes measured to better than 5% (ESA 1997); V -band magnitudes from Hipparcos, and K_S magnitudes from the 2MASS catalog and elsewhere in the literature; and, most importantly, all are metal rich with $[\text{Fe}/\text{H}] > +0.2$, assuming that the metallicities of these M dwarfs match those of their FGK binary companions. We designate these stars as our “high-metallicity” sample and list their properties in Table 1.

The positions of our high-metallicity M dwarfs in the $\{V - K_S, M_{K_S}\}$ plane form a locus that lies along the upper edge of our sample of M dwarfs in Figure 2, nearly parallel to the mean MS (solid line). Notably, our high-metallicity sample lies along the solar-composition B05 contour rather than above the $[\text{Fe}/\text{H}] = +0.2$ contour as would be expected. The B05 calibration therefore systematically underestimates the metallicities of these six metal-rich M dwarfs.

As a more quantitative assessment of the B05 calibration using the high-metallicity M dwarfs, we first restrict our analysis to the region of the $\{V - K_S, M_{K_S}\}$ plane over which the calibration is valid, namely $4 < M_{K_S} < 7.5$ and $2.5 < V - K_S < 6.0$ (B05). Four out of our six high-metallicity stars meet these criteria. B05 predict a mean $[\text{Fe}/\text{H}] = 0.0$ for these four stars, which is 0.32 dex lower than the mean metallicities of the FGK binary companions. This large discrepancy suggests that the B05 calibration contains a systematic error -0.32 dex for $[\text{Fe}/\text{H}] > 0$.

We performed an additional test by examining whether the B05 relationship could reproduce the spectroscopic metallicities of the stars in their calibration samples. Figure 3 shows the difference between the spectroscopic and photometric $[\text{Fe}/\text{H}]$ for the 19 calibration stars listed in Table 3 of B05, and the 29 metal-poor stars from Woolf & Wallerstein (2006). While the metallicities of the metal-poor stars are reproduced reasonably well, the values for the metal-rich calibration stars are systematically underestimated by as much as 0.33 dex. The inability of the B05 calibration to match the metallicities of their calibration sample is additional evidence for a large systematic error in the metallicity relationship, particularly for $[\text{Fe}/\text{H}] > 0$.

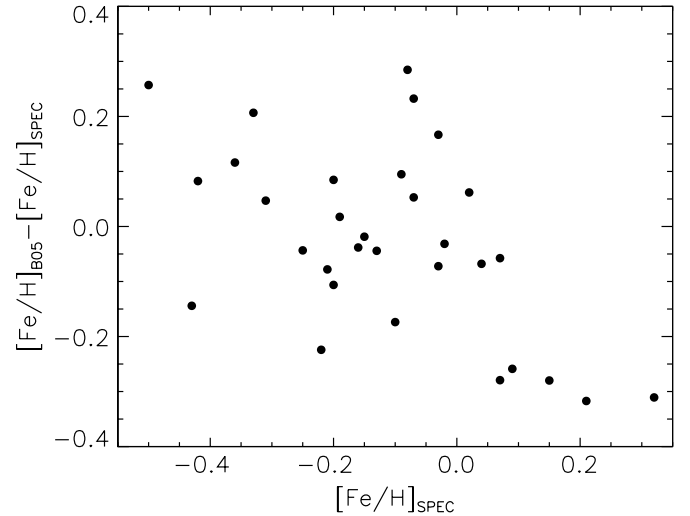


Figure 3. Difference between the spectroscopic and photometric $[\text{Fe}/\text{H}]$ for the sample of M dwarfs used to calibrate the B05 metallicity relationship. The B05 relationship systematically underestimates the metallicities of all calibration stars with $[\text{Fe}/\text{H}] > 0$.

We do not know the exact cause of this systematic error. One possible source may be the limited metallicity and color ranges spanned by the B05 calibration stars. Their first calibration sample comprises 29 late-type dwarfs that have spectroscopic metallicity measurements from Woolf & Wallerstein (2006). The second set of stars used for the B05 calibration consisted of 19 late K and M dwarfs with FGK primaries. Both of these samples are predominantly metal poor: only 3 of 29 stars in the Woolf & Wallerstein (2006) sample are metal-rich, and only 5 out of 19 stars among the second set have $[\text{Fe}/\text{H}] > 0$. Further, only one star in their entire sample, 55 Cnc B, has $[\text{Fe}/\text{H}] > +0.1$.

Another possible source of error is in the use of “visual magnitudes” (Gliese & Jahreiß 1991), rather than Johnson V -band magnitudes, for 7 out of the 19 M dwarfs in the B05 sample. The Gliese Catalog visual magnitudes were in many cases measured from photographic plates and therefore have non-negligible and poorly characterized uncertainties, especially when compared to the precision of modern V -band photometry. We searched the VizieR online catalog (Ochsenbein et al. 2000) for alternative photometric measurements for these seven stars, and located V -band photometry for six of them, mostly from the *Tycho/Hipparcos* and TASS Mark IV Survey catalogs (Perryman & ESA 1997; Droege et al. 2006). The difference between the V band and the visual magnitudes for these 6 B05 calibration stars has a median offset of 0.3 and an rms scatter of 0.7. This V -band magnitude offset is in the correct direction to account for part of the systematic error in the B05

Table 2
Properties of M Dwarf Planet Host Stars

Gliese Number	Spectral Type	M_{K_S}	$V - K_S$	ΔM_{K_S}	[Fe/H]	Planet Notes
876	M4	6.67	5.15	+0.75	+0.37	2 Jupiters + Super-Earth
832	M1.5	6.03	4.16	-0.13	-0.12	Single Jupiter
849	M3.5	5.80	4.82	+1.1	+0.58	Jupiter + Trend
436	M2.5	6.04	4.60	+0.54	+0.25	Neptune + Linear Trend
581	M3	6.87	4.73	-0.088	-0.10	Neptune + 2 Super-Earths
674	M2	6.57	4.53	-0.10	-0.11	Single Neptune
176	M2.5	5.77	4.34	+0.40	+0.18	Single Neptune

calibration at high metallicities, but the 0.7 mag scatter precludes the application of a simple correction factor.

3. EXAMINING THE METALLICITIES OF M DWARFS WITH PLANETS

Based on the results in the previous section, we conclude that there is a large systematic error in the B05 metallicity calibration, particularly for $[\text{Fe}/\text{H}] > 0$, and that there does not appear to be an abundance offset between M dwarfs and more massive stars. In light of this finding it is appropriate to re-examine the metallicities of the known M dwarf planet host stars, under the assumption that the metallicity distribution of stars in the solar neighborhood is independent of stellar mass.

We begin by noting that the stars in our high-metallicity sample form a well-defined locus in the $\{V - K_S, M_{K_S}\}$ plane (Figure 2), and this locus lies parallel and to the right of the mean MS. This suggests that the fundamental premise of the B05 calibration is valid: the metallicity of a given M dwarf should correlate with its distance from the MS.

Figure 4 shows the seven M dwarfs known to harbor one or more planets. An eighth M dwarf planet host star, Gl 317, is omitted because it lacks a reliable parallax measurement (Johnson et al. 2007). Stars with Jovian planets are designated by five-point stars, and those with Neptune-mass ($M_p \sin i < 30M_\oplus$) planets are shown as triangles. All seven M dwarf planet host stars lie near or above the mean MS in the $\{V - K_S, M_{K_S}\}$ plane. Four of the host stars—2/3 Jupiter-hosts and 2/4 Neptune-hosts—reside above the MS and are therefore likely metal-rich. Notably, the two metal-rich Jupiter-hosts also lie above the high-metallicity locus, indicating $[\text{Fe}/\text{H}] > +0.28$ based on the average value of the high-metallicity sample.

We now turn to a more quantitative approach to estimating the metallicities of the M dwarf planet hosts. As before, we assume the six-degree polynomial fit to the $\{V - K_S, M_{K_S}\}$ distribution of low-mass stars represents an isometallicity contour with $[\text{Fe}/\text{H}] = -0.05$, equal to the mean $[\text{Fe}/\text{H}]$ of the solar neighborhood. We then assume that $[\text{Fe}/\text{H}] \propto \Delta M_K$, where $\Delta M_K = MS - M_K$ is the distance away from the mean MS in the $\{V - K_S, M_{K_S}\}$ plane. We found that a linear relationship of the form

$$[\text{Fe}/\text{H}] = 0.56\Delta M_K - 0.05 \quad (1)$$

produces the best results, yielding a dispersion 0.06 dex, based on the rms scatter of the difference between the predicted and observed $[\text{Fe}/\text{H}]$ for our set of high-metallicity stars. Equation (1) is valid over the range $3.9 < V - K < 6.6$, which encompasses all known M dwarf planet hosts.

We applied Equation (1) to the 7 M dwarfs with known planets and precise parallaxes, and the results are given in the last column of Table 2. As in our qualitative analysis, we find that four of the seven M dwarf planet hosts are metal rich, and

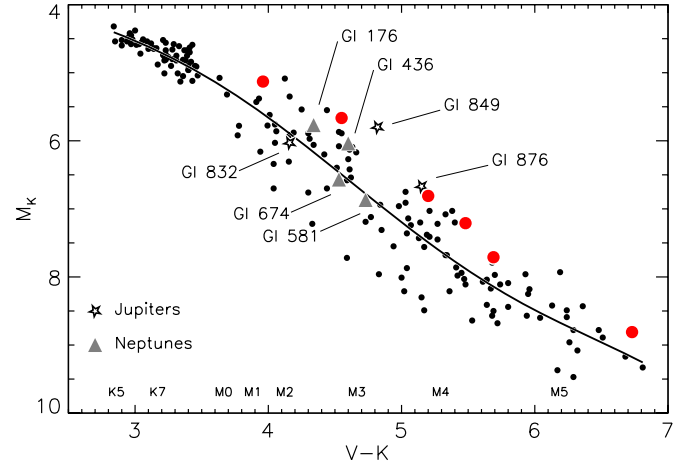


Figure 4. Nearby low-mass stars in the $\{V - K_S, M_{K_S}\}$ plane, along with M dwarfs known to harbor at least one planet. The small black circles a volume-limited sample of K and M dwarfs. The solid line is a fifth-order polynomial fit to the mean MS. The large filled circles are the positions of a sample of high-metallicity M dwarfs, with spectroscopic $[\text{Fe}/\text{H}]$ measured from their FGK binary companions. Five-point stars are M dwarfs with at least one Jovian planet, and the triangles are stars with at least one Neptune-mass planet. The $V - K_S$ colors of various spectral types are listed at the bottom of the figure. (A color version of this figure is available in the online journal.)

of these Gl 849 and Gl 876 have $[\text{Fe}/\text{H}] > +0.3$. The three stars with subsolar metallicities are only slightly more metal poor than the average metallicity of the solar neighborhood—all three have $[\text{Fe}/\text{H}] > -0.15$. However, we note that we had to extrapolate beyond our data for the region just below the MS. The mean and median metallicities for the M dwarfs with planets are $[\text{Fe}/\text{H}] = +0.16$ and $+0.19$, respectively, which is comparable to the mean metallicity for the sample of known FGK dwarfs with planets ($[\text{Fe}/\text{H}] = +0.15$).

4. SUMMARY AND DISCUSSION

Based on the results of Doppler-based planet searches, giant planet occurrence has been demonstrated to correlate with stellar mass and metallicity ($[\text{Fe}/\text{H}]$). For FGK dwarfs, $[\text{Fe}/\text{H}]$ is typically measured using LTE spectroscopic model fits to observed, high-resolution spectra, yielding measurements with a precision of ≈ 0.05 dex (Valenti & Fischer 2005). However, the complex spectra of low-mass M dwarfs precludes the use of standard LTE spectral modeling, and knowledge of the metallicity distribution of M dwarfs rests primarily on the B05 photometric calibration. Based on their calibration, B05 reported a systematic metallicity discontinuity for spectral types later than $\sim K7V$, corresponding to stellar masses $M_* \lesssim 0.5 M_\odot$. This finding begs the question: is the deficit of Jovian planets around M dwarfs due to their intrinsically low stellar masses, or instead due to their systematically lower metallicities?

We have addressed this question by studying several samples of low-mass stars in the $\{V - K_S, M_{K_S}\}$ plane. Our volume-limited sample of M dwarfs exhibits large scatter about the MS, which is attributable to metallicity effects on the stars' spectral energy distributions. Our second set of low-mass stars consists of six M dwarfs with wide, FGK binary companions that have spectroscopic metallicities $[\text{Fe}/\text{H}] > +0.25$ dex.

We find that the B05 calibration underestimates the metallicities of our high-metallicity stars by an average of 0.32 dex, and the B05 solar-abundance contour lies well above the mean MS of our volume-limited set. Based on these results, we conclude

that the systematic metallicity offset for M dwarfs reported by B05 is a result of an error in their calibration, rather than a reflection of the true metallicity distribution of low-mass stars. It is therefore more likely that the decreased number of Jovian planets around M dwarfs is a reflection of their lower stellar masses, rather than a metallicity effect.

The cause of the systematic error in the B05 photometric metallicity calibration is unclear. But the underlying concept that metallicity is directly proportional to height above the MS in the $\{V - K_S, M_{K_S}\}$ plane is valid: our sample of six high-metallicity M dwarfs form a locus that runs along the upper edge of the MS in Figure 2, offset from the mean MS by $\Delta M_K \approx 0.5$. To estimate the metallicities of seven M dwarfs known to harbor planets, we derive a new photometric calibration based on a polynomial fit to the mean MS of our volume-limited sample of low-mass stars, and the locus defined by our set of high-metallicity sample. Our calibration reveals that planets around M dwarfs are found preferentially around metal-rich stars, a result similar to the metallicity bias observed for FGK planet host stars (Santos et al. 2004; Fischer & Valenti 2005).

In addition to planet occurrence, stellar metallicity also correlates with the physical properties of exoplanets. For example, the relationship between minimum planet mass ($M_P \sin i$) and host-star metallicity has recently received attention from several recent studies (Sousa et al. 2008; Howard et al. 2009). Sousa et al. studied a large sample of stars with and without planets and found a mean metallicity $[\text{Fe}/\text{H}] = -0.21$ for stars that harbor at least one Neptune ($M_P \sin i \lesssim 0.1 M_{\text{Jup}}$) but no Jupiters ($M_P \sin i > 0.2 M_{\text{Jup}}$). Their result implies that Neptune-mass planets form preferentially around metal-poor stars, in contrast to stars with giant planets (mean $[\text{Fe}/\text{H}] +0.15$). They also noticed an offset between the metallicities of stars with only Neptunes compared to stars with both Neptunian and Jovian planets, which have a mean $[\text{Fe}/\text{H}] = -0.03$. Sousa et al. summarized their result as an observed increase in metallicity as a function of the ratio of the number of Jupiters to Neptunes in a planetary system.

However, four out of the six stars in the Sousa et al. Neptune-only sample were M dwarfs with metallicity estimates primarily from B05. Using our metallicity estimates for the M dwarfs in their sample, we find that their Neptune-only sample has a mean metallicity $[\text{Fe}/\text{H}] = -0.03$, which is equal to the average metallicity of stars with both Neptunes and Jupiters. Thus, while the Neptune-hosts still appear to be metal poor compared to the Jupiter-hosts, there no longer appears to be a metallicity offset between stars with Neptunes only and those with both Neptunes and Jupiters. As additional low-mass planets are discovered, the trends between stellar metallicity and the occurrence of Neptunes and sub-Neptune-mass planets will come into better focus (Mayor et al. 2009; Howard et al. 2009).

Finally, it is important to caution the reader that our metallicity calibration is meant only as a tool to gain a sense of the metallicity distribution of M dwarfs with planets, and is currently restricted to a limited color and magnitude range. For example, our rough calibration was extrapolated to the region just below the mean MS. We feel this extrapolation was safe for our study, but problems could arise if extrapolated further into the metal-poor regime. We are currently obtaining spectroscopic observations at Lick Observatory of a larger sample of FGK+M

binaries in order to derive a more thorough photometric calibration extending over a broader region of the $\{V - K_S, M_{K_S}\}$ plane.

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REFERENCES

- Bean, J. L., Benedict, G. F., & Endl, M. 2006, *ApJ*, **653**, L65
 Bonfils, X., Delfosse, X., Udry, S., Santos, N. C., Forveille, T., & Ségransan, D. 2005, *A&A*, **442**, 635
 Butler, R. P., Johnson, J. A., Marcy, G. W., Wright, J. T., Vogt, S. S., & Fischer, D. A. 2006, *PASP*, **118**, 1685
 Carpenter, J. M. 2001, *AJ*, **121**, 2851
 Delfosse, X., Forveille, T., Ségransan, D., Beuzit, J.-L., Udry, S., Perrier, C., & Mayor, M. 2000, *A&A*, **364**, 217
 del Peloso, E. F., da Silva, L., Porto de Mello, G. F., & Arany-Prado, L. I. 2005, *A&A*, **440**, 1153
 Droege, T. F., Richmond, M. W., Sallman, M. P., & Creager, R. P. 2006, *PASP*, **118**, 1666
 Endl, M., Cochran, W. D., Tull, R. G., & MacQueen, P. J. 2003, *AJ*, **126**, 3099
 ESA 1997, VizieR Online Data Catalog, **1239**, 0
 Fischer, D. A., & Valenti, J. 2005, *ApJ*, **622**, 1102
 Gliese, W., & Jahreiß, H. 1991, Preliminary Version of the Third Catalogue of Nearby Stars, Tech. rep.
 Gustafsson, B. 1989, *ARA&A*, **27**, 701
 Hansen, C. J., & Kawaler, S. D. 1994, *Stellar Interiors: Physical Principles, Structure, and Evolution*, XIII (Berlin: Springer)
 Haywood, M. 2001, *MNRAS*, **325**, 1365
 Howard, A. W., et al. 2009, *ApJ*, **696**, 75
 Ida, S., & Lin, D. N. C. 2004, *ApJ*, **616**, 567
 Ida, S., & Lin, D. N. C. 2005, *ApJ*, **626**, 1045
 Johnson, J. A., Butler, R. P., Marcy, G. W., Fischer, D. A., Vogt, S. S., Wright, J. T., & Peek, K. M. G. 2007, *ApJ*, **670**, 833
 Kennedy, G. M., & Kenyon, S. J. 2008, *ApJ*, **673**, 502
 Laughlin, G., Bodenheimer, P., & Adams, F. C. 2004, *ApJ*, **612**, L73
 Leggett, S. K. 1992, *ApJS*, **82**, 351
 Lovis, C., & Mayor, M. 2007, *A&A*, **472**, 657
 Maness, H. L., Marcy, G. W., Ford, E. B., Hauschildt, P. H., Shreve, A. T., Basri, G. B., Butler, R. P., & Vogt, S. S. 2007, *PASP*, **119**, 90
 Martinache, F., Rojas-Ayala, B., Ireland, M. J., Lloyd, J. P., & Tuthill, P. G. 2009, *ApJ*, **695**, 1183
 Mayor, M., et al. 2009, *A&A*, **493**, 639
 Ochsenbein, F., Bauer, P., & Marcout, J. 2000, *A&AS*, **143**, 23
 Perryman, M. A. C., et al. 1997, *A&A*, **323**, 49
 Reid, I. N., Kilkeny, D., & Cruz, K. L. 2002, *AJ*, **123**, 2822
 Reid, I. N., Turner, E. L., Turnbull, M. C., Mountain, M., & Valenti, J. A. 2007, *ApJ*, **665**, 767
 Sandage, A., Lubin, L. M., & VandenBerg, D. A. 2003, *PASP*, **115**, 1187
 Santos, N. C., Israelian, G., & Mayor, M. 2004, *A&A*, **415**, 1153
 Skrutskie, M. F., et al. 2006, *AJ*, **131**, 1163
 Sousa, S. G., et al. 2008, *A&A*, **487**, 373
 Valenti, J. A., & Fischer, D. A. 2005, *ApJS*, **159**, 141
 van Altena, W. F., Lee, J. T., & Hoffleit, E. D. 1995,
 van Leeuwen, F. H. 2007, *The New Reduction of the Raw Data, ASSL* (Dordrecht: Springer), 350
 Woolf, V. M., & Wallerstein, G. 2006, *PASP*, **118**, 218